Proposed method for groundwater vulnerability mapping in carbonate (karstic) aquifers: the COP method

Application in two pilot sites in Southern Spain

J. M. Vías · B. Andreo · M. J. Perles · F. Carrasco · I. Vadillo · P. Jiménez

Abstract The 'COP method' has been developed for the assessment of intrinsic vulnerability of carbonate aquifers in the frame of the European COST Action 620. This method uses the properties of overlying layers above the water table (*O* factor), the concentration of flow (*C* factor) and precipitation (*P* factor) over the aquifer, as the parameters to assess the intrinsic vulnerability of groundwater. This method considers karst characteristics, such as the presence of swallow holes (*C* factor) and their catchment areas as well as karstic landforms, as factors which decrease the natural protection provided by overlying layers (*O* factor). The *P* factor allows for consideration of the spatial and temporal variability of precipitation, which is considered the transport agent of contamination. Two carbonate aquifers in the South of Spain, Sierra de Líbar (a conduit flow system) and Torremolinos (a diffuse flow system), have been selected for the application and validation of the method and the results have been compared with three methods widely applied in different aquifers around the world (AVI, GOD and DRASTIC). Comparisons with these methods and validation tools (hydrogeological data and tracer test) show the advantages of the COP method in the assessment of vulnerability of karstic groundwaters.

Résumé La méthode "COP" a été développée pour évaluer la vulnérabilité intrinsèque des aquifères carbonatés dans le cadre du programme COST Action 620 de l'Union Européenne. Cette méthode utilise les propriétés des couches situées au dessus de la nappe aquifère (facteur *O*), la concentration de l'écoulement (facteur *C*) et les précipitations (facteur *P*) au dessus de l'aquifère, comme les paramètres de l'évaluation de la vulnérabilité intrinsèque des eaux souterraines. Cette méthode considère les caractéristiques du karst, comme la présence de dépressions en surface (facteur *C*) et l'étendue de leur bassin versant, ainsi que les formes du paysage karstique, comme des facteurs qui diminuent la protection naturelle apportée par les couches du dessus (facteur *O*). Le facteur *P* permet de considérer la variabilité spatiale et temporelle des précipitations, en tant qu'agent de transport de la contamination. Deux aquifères carbonatés du Sud de l'Espagne, la Sierra de Libar (un système à conduit) et Torremolinos (un système d'écoulement diffus), ont été sélectionnés pour l'application et la validation de cette méthode, et les résultats ont été comparés avec trois méthodes assez utilisées sur d'autres aquifères dans le monde (AVI, GOD et DRASTIC). Les comparaisons avec ces trois méthodes et les outils de validation (données hydrogéologues et tests de traçage) montrent les avantages de la méthode COP lors de l'évaluation de la vulnérabilité des eaux souterraines karstiques.

Resumen El método COP ha sido desarrollado para evaluar y cartografiar la vulnerabilidad intrínseca de los acuíferos carbonáticos en el marco de la Acción Europea COST 620. El método utiliza los siguientes factores: capacidad de protección de la zona no saturada (*O*), concentración de flujos en superficie (*C*) y precipitación (*P*). El método COP tiene en cuenta características tales como la presencia de sumideros kársticos y su cuenca de alimentación y formas exokársticas, porque disminuyen la capacidad de protección natural del agua subterránea dada por las capas suprayacentes (factor *O*). El factor *P* tiene en cuenta la variabilidad espacial y temporal de la precipitación, por ser el principal agente que transporta los contaminantes hasta el agua subterránea. El método COP se ha aplicado en dos acuíferos del Sur de España, Sierra de Líbar (acuífero kárstico de flujo por conductos) y Torremolinos (acuífero fisurado de flujo difuso), y los resultados en ambos acuíferos han sido comparados con los resultados obtenidos mediante otros métodos ampliamente utilizados en el mundo (DRASTIC, GOD y AVI). La comparación realizada y las técnicas de validación (datos hidrogeológicos y ensayo de trazadores) ha permitido determinar las ventajas que supone utilizar el método COP en los acuíferos carbonáticos.

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Introduction

Since Margat (1968) and Albinet and Margat (1970) introduced the concept of the vulnerability of groundwater to contamination, the international scientific community has shown an increasing interest in groundwater protection (Foster and Hirata 1988; Adams and Foster 1992; Drew and Hötzl 1999; Zwahlen 2004). Many methods have been proposed for groundwater vulnerability mapping, including; DRASTIC (Aller et al. 1987), GOD (Foster 1987), AVI (Van Stempvoort et al. 1993), and SINTACS (Civita 1994). A thorough overview of existing methods is given in Vrba and Zaporozec (1994) and in Gogu and Dassargues (2000). These methods have been mainly applied to groundwater protection in porous aquifers, except the EPIK (Doerfliger and Zwahlen 1998; Doerfliger et al. 1999) and PI (Goldscheider et al. 2000) methods which were specifically developed for the assessment of vulnerability in karstic areas.

World wide, groundwater from karst aquifers is considered an important resource and is extensively used for water supply. In Europe, carbonate terrains occupy 35% of the land-surface and in some countries karst groundwater contributes up to 50% to the total drinking water supply; in many regions it is the only available fresh water resource (European Commission 1995). Karst aquifers are particularly vulnerable to contamination due to thin soils, flow concentration within the epikarst and concentrated recharge via swallow holes. As a result, contaminants may easily reach the groundwater and be rapidly transported in karst conduits over large distances (Goldscheider 2005). In karst aquifers, the residence time of contaminants is often short and natural attenuation processes do not occur effectively. Recognising these issues, the Directorate General for Science, Research and Development of the European Commission supported COST Action 620 (COST is the acronym for "COoperation in Science and Technology) which considered "Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers" and ran between 1997 and 2003. This Action contributed to the development of the European Water Framework Directive 2000/60/EC for river basin management (European Commission 2000) and the Directive COM(2003)550 (European Commission 2003) for protection of groundwater from pollution (known as the *Groundwater Daughter Directive*).

Two classes of vulnerabilities have been distinguished (Daly et al. 2002): intrinsic and specific vulnerability. Intrinsic vulnerability is the susceptibility of groundwater to contaminants generated by human activities and takes into account the hydrogeological characteristics of an area, but is independent of the nature of the contaminant and the contamination scenario. Specific vulnerability takes into account the physical-chemical properties of contaminants and their relationship to the physical-chemical properties of the hydrogeological system.

In addition, according to the Origin-Pathway-Target model (Daly et al. 2002), the target for vulnerability mapping may be either the groundwater resource or the source of water (springs/pumping wells) used for water supply. For resource vulnerability, the target is the groundwater surface within the aquifer and only the vertical pathway through overlying layers is considered. For source vulnerability, water in wells or springs is the target; consequently, this includes additionally horizontal flow within the aquifer. A European Approach to vulnerability mapping in karst aquifers has been developed in the framework of COST Action 620, and considered four factors (Daly et al. 2002; Goldscheider and Popescu 2004): overlying layers (O factor), concentration of flow (C factor), precipitation regime (P factor) and karst network development (K factor). Resource vulnerability maps may be prepared by a combination of the O, C and P factors whereas for source vulnerability maps, the addition of the K factor is required. Originally, Daly et al. (2002) developed a conceptual framework but did not propose detailed guidelines, tables or formulae for vulnerability assessment. They highlighted the need for developing methods, which facilitated flexible application in different European regions using available data and accommodating varying climatic conditions. Intrinsic vulnerability maps are used as environmental management tools so must be capable of validation with natural or artificial tracers in order to ensure that the conceptual understanding of prevailing hydrogeological conditions are valid (Bruyère et al. 2001; Jeannin et al. 2001; Goldscheider et al. 2001; Perrin et al. 2004).

Conventional methods (i.e. DRASTIC, AVI, GOD, SINTACS) are able to distinguish degrees of vulnerability at regional scales where different lithologies exist (Vías et al. 2005), but they are much less effective at assessing vulnerability in carbonate aquifers as they do not take into account the peculiarities of karst. This paper proposes a new method (COP) that considers the special hydrogeological properties of karst. The method can be applied in different climatic conditions and different types of carbonate aquifers (diffuse and conduit flow systems). In addition, the COP method uses variables, parameters and factors in line with those proposed in the European Approach (Daly et al. 2002; Zwahlen 2004) and it can be applied using different levels of available data. A quantification and category system for each parameter has been established, using the combination and weighting of variables. The proposed method has been used to map the intrinsic vulnerability of two carbonate aquifers in Southern Spain with differing climate, hydrogeology and geology. Both aquifers have been previously investigated using other vulnerability mapping methods (Longo et al. 2001; Brechenmacher 2002; Vías et al. 2005; Andreo et al. 2005) and some validation of the results has been carried out. Consequently, it is possible to compare results and to demonstrate the effectiveness of the COP method in karst areas, particularly within Mediterranean aquifers.

Characteristics of the COP method

The COP acronym comes from the three initials of the factors used: flow Concentration, Overlying layers and Precipitation (Fig. 1). The conceptual basis of this method, according to the European Approach (Daly et al. 2002; Goldscheider and Popescu 2004), is to assess the natural protection of groundwater (O factor) determined by the properties of overlying soils and the unsaturated zone, and also to estimate how this protection can be modified by the infiltration process – diffuse or concentrated – (C factor) and the climatic conditions (P factor – precipitation).

The O factor (overlying layers)

The O factor considers the protection provided to the aquifer by the physical properties and thickness of the layers above the saturated zone. Daly et al. (2002) proposed subdivision into four layers: topsoil, subsoil, non-karstic rocks and unsaturated karstic rocks. In the proposed COP method only two layers with important hydrogeological roles are used in order to evaluate the O factor: Soils [O_S] and the lithological layers of the unsaturated zone [O_L].

The *soil subfactor* [O_S] deals with the biologically active part of the subsurface, where attenuation processes occur and as a consequence, when present, should be taken into account in vulnerability mapping. Several parameters are considered in the evaluation of the soil subfactor (Fig. 1 – Tables I and II): texture, grain size distribution and thickness, the last being highly variable in Mediterranean areas. The *lithology subfactor* [O_L] reflects the attenuation capacity of each layer within the unsaturated zone. The assessment criteria for its quantification are the type of rock (which determines its hydrogeological characteristics, mainly effective porosity and hydraulic conductivity) and the degree of fracturing (ly), the thickness of each layer (m) and any confining conditions (cn) (Fig. 1 – Tables III–V). Successive summing of the products from the multiplication of thickness and lithology of each layer, yields an index which is associated with protection (Layer index $= \sum(\mathrm{ly} \cdot m)$). The concept of adding layers is based on the AVI method (Van Stempvoort et al. 1993) and PI method (Goldscheider et al. 2000).

The “cn” parameter is a weighting coefficient for the layer index similar to the GOD method (Foster 1987) and the PI method (Goldscheider et al. 2000). The values assigned to the “cn” parameter (Fig. 1 – Table V) give the highest protection to the confined aquifer whereas an unconfined aquifer is not affected by this parameter ($\mathrm{cn} = 1$).

The attenuation capacity increases with the sum of the protective layers. Thus, an O score is obtained by adding the subfactors *soil* [O_S] and *lithology* [O_L] (Fig. 1 – Table VI), yielding a corresponding *protection value*. The lowest values of the O factor (higher vulnerability) correspond to areas where carbonate materials outcrop and where the soil is poorly developed or absent. Moderate and High protection values (lower vulnerability), derived from higher O scores, are representative of areas where the degree of protection is high, either due to the presence of soil or of low-permeability lithologies.

The C factor (flow concentration)

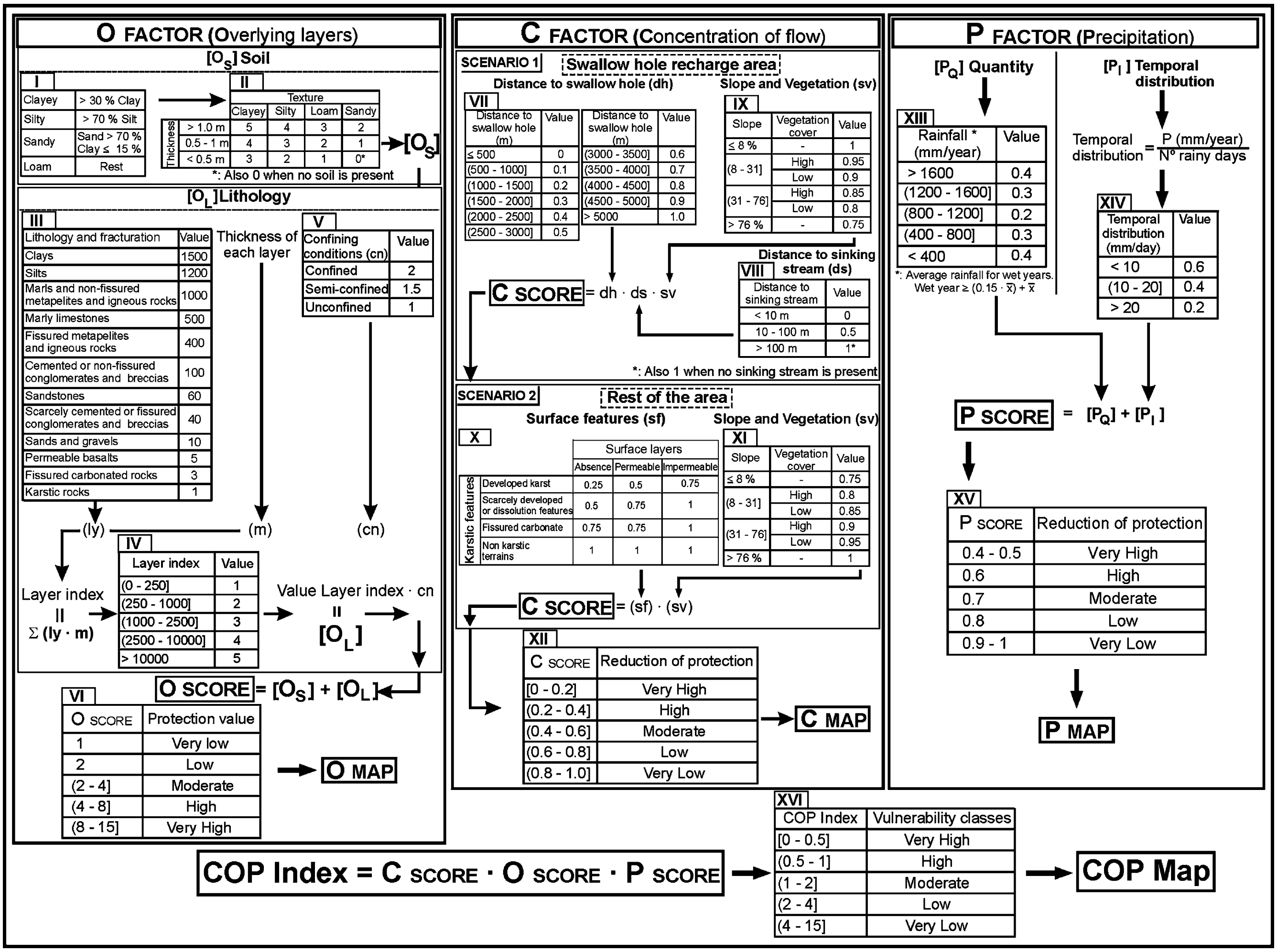
The O factor describes the vulnerability of groundwater from contamination where infiltration through the unsaturated zone is diffuse. The C factor is a modifier of the O factor (overlying layers) and represents the potential for water to bypass the protection provided by the overlying layers (Daly et al. 2002). The C factor represents the degree to which precipitation at or near aquifer outcrop is concentrated into a swallow hole, bypassing the unsaturated zone. This is based on the PI method (Goldscheider et al. 2000) and the EPIK method (Doerfliger and Zwahlen 1998).

Two scenarios may be differentiated (Fig. 1):

Scenario 1: This describes the situation within a catchment covered by a low permeability layer, where surface runoff flows either into a swallow hole or an area of concentrated infiltration such as the foot of a slope. That is when both allogenic and autogenic recharge within the catchment is concentrated into a karst feature which results in the bypass of the unsaturated zone. The evaluation of the C factor in this scenario considers four variables: the distance from the recharge area to the swallow hole (dh) and to the sinking stream (ds), and the influence of slope (s) and vegetation (v). The vulnerability of the aquifer reduces with increasing distance between the recharge area and the swallow hole or the sinking stream (Fig. 1 – Tables VII and VIII).

The assessment of vegetation cover (v) considers the percentage of catchment area cover that is most likely to affect the infiltration-runoff regime (Fig. 1 – Table IX). Low vegetation cover is considered to be less than 20–30% of a given surface area. Four ranges of topographic slope (s) are positively correlated with runoff. The combination of slope and vegetation provide the value for the slope-vegetation parameter (sv) (Fig. 1 – Table IX). The values of “sv” show that when the slope increases and vegetation is scarce, the vulnerability increases giving values of “sv” close to 1. This means that recharge flows more easily to the swallow hole resulting in shorter travel times to the water table. The C score, under these recharge conditions, is obtained by multiplying the values of the parameter for slope and vegetation (sv) by those for the distances from recharge area to the swallow hole (dh) or the sinking stream (ds).

Scenario 2: This describes the situation in areas where autogenic recharge occurs but not as concentrated infiltration via a swallow hole or at the foot of a slope. The C score under this situation is evaluated by the combination of only three variables: surface features (sf), slope (s) and vegetation (v).



I

Clayey	> 30 % Clay
Silty	> 70 % Silt
Sandy	Sand > 70 % Clay ≤ 15 %
Loam	Rest

II

Thickness	Texture: Clayey	Silty	Loam	Sandy
> 1.0 m	5	4	3	2
0.5 - 1 m	4	3	2	1
< 0.5 m	3	2	1	0*

*: Also 0 when no soil is present

III

Lithology and fracturation	Value
Clays	1500
Silts	1200
Marls and non-fissured metapelites and igneous rocks	1000
Marly limestones	500
Fissured metapelites and igneous rocks	400
Cemented or non-fissured conglomerates and breccias	100
Sandstones	60
Scarcely cemented or fissured conglomerates and breccias	40
Sands and gravels	10
Permeable basalts	5
Fissured carbonated rocks	3
Karstic rocks	1

V

Confining conditions (cn)	Value
Confined	2
Semi-confined	1.5
Unconfined	1

IV

Layer index	Value
[0 - 250]	1
(250 - 1000]	2
(1000 - 2500]	3
(2500 - 10000]	4
> 10000	5

VI

O SCORE	Protection value
1	Very low
2	Low
(2 - 4]	Moderate
(4 - 8]	High
(8 - 15]	Very High

VII

Distance to swallow hole (m)	Value	Distance to swallow hole (m)	Value
≤ 500	0	(3000 - 3500]	0.6
(500 - 1000]	0.1	(3500 - 4000]	0.7
(1000 - 1500]	0.2	(4000 - 4500]	0.8
(1500 - 2000]	0.3	(4500 - 5000]	0.9
(2000 - 2500]	0.4	> 5000	1.0
(2500 - 3000]	0.5		

IX

Slope	Vegetation cover	Value
≤ 8 %	-	1
(8 - 31]	High	0.95
	Low	0.9
(31 - 76]	High	0.85
	Low	0.8
> 76 %	-	0.75

VIII

Distance to sinking stream	Value
< 10 m	0
10 - 100 m	0.5
> 100 m	1*

*: Also 1 when no sinking stream is present

X

Karstic features	Surface layers: Absence	Permeable	Impermeable
Developed karst	0.25	0.5	0.75
Scarcely developed or dissolution features	0.5	0.75	1
Fissured carbonate	0.75	0.75	1
Non karstic terrains	1	1	1

XI

Slope	Vegetation cover	Value
≤ 8 %	-	0.75
(8 - 31]	High	0.8
	Low	0.85
(31 - 76]	High	0.9
	Low	0.95
> 76 %	-	1

XII

C SCORE	Reduction of protection
[0 - 0.2]	Very High
(0.2 - 0.4]	High
(0.4 - 0.6]	Moderate
(0.6 - 0.8]	Low
(0.8 - 1.0]	Very Low

XIII

Rainfall * (mm/year)	Value
> 1600	0.4
(1200 - 1600]	0.3
(800 - 1200]	0.2
(400 - 800]	0.3
< 400	0.4

*: Average rainfall for wet years. Wet year ≥ $(0.15 \cdot \bar{x}) + \bar{x}$

XIV

Temporal distribution (mm/day)	Value
< 10	0.6
(10 - 20]	0.4
> 20	0.2

XV

P SCORE	Reduction of protection
0.4 - 0.5	Very High
0.6	High
0.7	Moderate
0.8	Low
0.9 - 1	Very Low

XVI

COP Index	Vulnerability classes
[0 - 0.5]	Very High
(0.5 - 1]	High
(1 - 2]	Moderate
(2 - 4]	Low
(4 - 15]	Very Low

Fig. 1 Diagram of the COP method, showing the differentiation of the *C*, *O* and *P* factors (containing numeric evaluation Tables I–XVI, described in the text)

The *Surface features* parameter (Fig. 1 – Table X) considers those geomorphological features specific to carbonate rocks and the presence or absence of any overlying layers (permeable or impermeable) which determine the importance of runoff and/or infiltration processes.

The evaluation of vegetation and slope (Fig. 1 – Table XI) is carried out in the opposite way to Scenario 1, because when slopes are steeper and vegetation is absent, runoff (and potential contaminants) flow away from the aquifer and not toward features such as swallow holes. This situation is common on the slopes of carbonate aquifers in mountainous regions.

To obtain the *C* score in Scenario 2, the slope-vegetation (*sv*) parameter is weighted by the surface features (*sf*).

For example, zones with concentrated infiltration via swallow holes where the natural protection given by the *O* factor is bypassed, have low values for the *C* factor (Fig. 1 – Table XII). Conversely, where diffuse infiltration occurs in the absence of karst features or where there is runoff out of the aquifer, then the aquifer retains some natural protection.

The P factor (precipitation)

According to Daly et al. (2002) this factor includes the quantity of precipitation and factors which influence the rate of infiltration, i.e. frequency, temporal distribution, duration and intensity of extreme rainfall events. These factors help determine the ability of precipitation to transport contaminants from the surface to the groundwater; the greater its capacity to transport contaminants towards the aquifer, the higher the implied vulnerability.

The *P* factor is evaluated by two subfactors: *Quantity* of precipitation $[P_Q]$ and *temporal distribution* of precipitation $[P_I]$.

The $[P_Q]$ subfactor (Fig. 1 – Table XIII) describes the effect of rainfall quantity and the annual recharge on groundwater vulnerability. It corresponds to the mean annual rainfall of a historical series of wet years. Several vulnerability methods (PI, DRASTIC) consider groundwater

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protection to decrease (or vulnerability to increase) with increasing recharge as infiltration occurs more rapidly. Conversely, higher rates of recharge provide higher dilution and consequently the vulnerability decreases. The SINTACS method (Civita 1994) proposes a reduction in vulnerability when recharge is higher than 300–400 mm/year. In carbonate aquifers around the Mediterranean, the annual average recharge ranges between 35 and 55% of annual precipitation (López-Geta et al. 2004). Therefore it can be established that an increase in precipitation up to around 800–1,200 mm increases vulnerability because the transit time for contaminants, from the surface to groundwater, is likely to be more important than the dilution process. When annual precipitation exceeds 800–1,200 mm, the dilution of potential contaminant is likely to be the dominant process and consequently the protection given by the O factor is less modified.

The $[P_I]$ subfactor concerns the temporal distribution of precipitation in a certain period of time and thus is indicative of the intensity of precipitation. This subfactor enables a comparison to be made between zones within Europe, where rainfall and intensity conditions are highly variable. For example, in Mediterranean areas, precipitation is more intense than in central and northern Europe. For the estimation of this subfactor, two variables are considered for a wet year, the mean annual precipitation and the number of rainy days (Fig. 1 – Table XIV). It follows therefore, that values assigned to the $[P_I]$ subfactor are greater with higher totals of annual precipitation and lower number of rainy days. This results in larger amounts of recharge that facilitates rapid infiltration through fissures or karst conduits, thus increasing groundwater vulnerability. The greater the daily rainfall, the greater the amounts of runoff towards swallow holes that favour concentrated infiltration. Where infiltration is diffuse and slow, the $[P_I]$ sub-factor is low; usually in such circumstances the volumes of recharge are relatively small.

Higher values of the P factor (Fig. 1 – Table XV) indicate a lower impact on the level of protection afforded by the O factor. However lower values indicate that precipitation, as a function of quantity and intensity, diminishes the protection afforded by the O factor and increases groundwater vulnerability.

COP vulnerability index

The factors of the COP method have been combined to evaluate the intrinsic vulnerability of a groundwater resource, as proposed in the following formula:

$$\text{COP Index} = C \cdot O \cdot P$$

The final numerical representations of the C, O and P factors (the C, O and P scores) are multiplied, because each one is considered to impact on the assessment of vulnerability of karst aquifers.

Within the COP method, the values for the intrinsic vulnerability index range between 0 and 15 (Fig. 1 – Table XVI). Following the proposal by Vrba and Zaporozec (1994), the values for this index are grouped into five vulnerability classes (Very High, High, Moderate, Low and Very Low vulnerability).

The COP index values are really a modification of the values for the O factor, consisting of a reclassification of groups and their associated vulnerability. The extreme classes of the O factor have been split and their values reclassified. The interval limits for the Very High and High classes are assigned mainly depending on the influence of the C factor on carbonate rocks, and to a lesser degree on that of the P factor. Those of the Very Low class correspond to zones in which the C and P factors have little influence on protection. The Moderate and Low classes refer to zones where potential protection is low to average, in which the C and P factors do not have a decisive influence on vulnerability (which they do in the High and Very High classes).

Vulnerability mapping of pilot sites

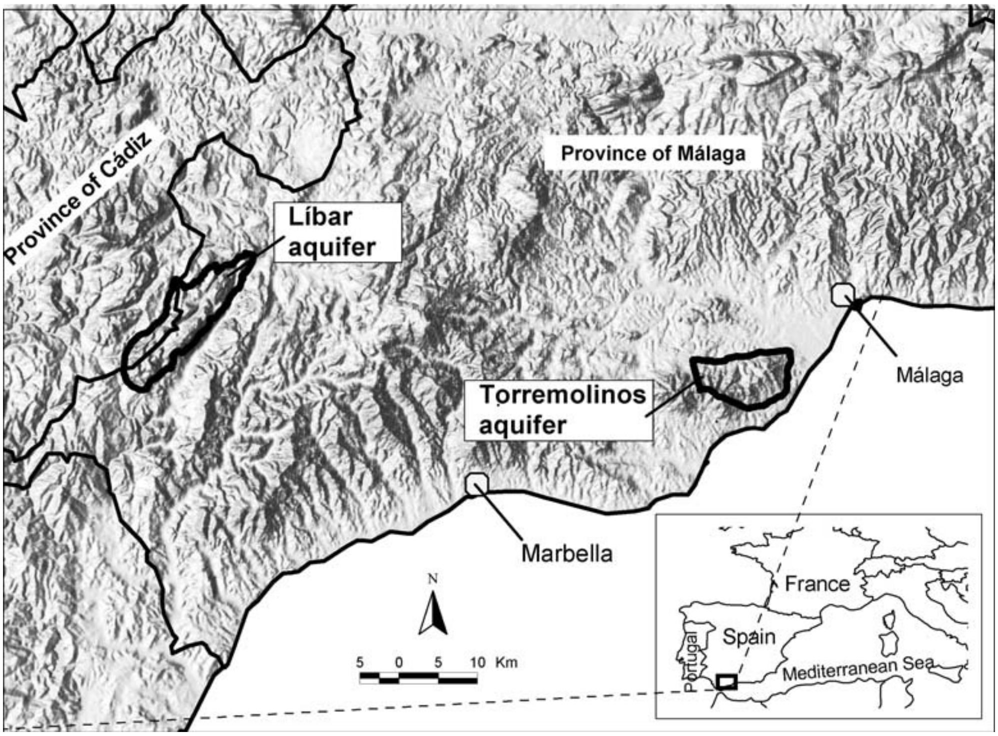
The COP method has been applied in two aquifers in the South of Spain, the aquifers of Sierra de Líbar and Torremolinos (Fig. 2). The first is a karstic aquifer with a conduit flow system, whilst the second is a fissured carbonate aquifer with a diffuse flow system. Common methods of intrinsic vulnerability assessment have been applied in both aquifers (Longo et al. 2001; Brechenmacher 2002; Vías et al. 2005).

Characteristics of the pilot aquifers

The Sierra de Líbar aquifer covers a surface area of around 90 km^2, between the provinces of Málaga and Cádiz, with an average rainfall of 1,500 mm. It is made up of Jurassic limestones, with a thickness of over 400 m overlain by Cretaceous marls and marly-limestones (Fig. 3). The geological structure comprises N40E trending anticlines of Jurassic limestones and synclines of cretaceous materials; although locally the cores of the synclines are covered by Quaternary sediments. Soils overlying the limestones are absent, with the exception of poljes developed in synclinal structures where Cretaceous marls and marly-limestones outcrop. The lithological and geological structures result in steep slopes and a flat relief in the central sector which has an abundance of karstic landforms (Delannoy 1987), including karren, sinkholes and poljes with swallow holes. In the north of the aquifer there are a large number of karst conduits into which sinking streams pass directly into the limestone. Most of the discharge from the aquifer is via springs located on the eastern border. These springs exhibit karstic behaviour, responding rapidly to precipitation, with sharp changes in flow (Benavente and Mangin 1984; Jiménez et al. 2004).

The Torremolinos carbonate aquifer (56 km^2) is some 15 km to the southwest of the city of Málaga (Fig. 2) and is made up of Triassic marbles (Fig. 4), with a thickness of 600 m and overlay Paleozoic metapelites (Andreo

Fig. 2 Geographical location of Sierra de Líbar and Torremolinos aquifers



et al. 1997). The marbles form ESE-WNW trending isoclinal folds, which have subsequently been subjected to faulting. At the northern and eastern borders of the system, Neogene-Quaternary rocks overlay the marbles. The predominant soil types are antrosol, regosol and calcisol, overlaying Pliocene marls. These soils are less than 70 cm in thickness, whereas the leptosol which overlays the Triassic marbles, is less than 30 cm thick (ICONA 1991). The topography is very steep with the exception of northern and eastern parts of the aquifer region. The average rainfall is 600 mm per year. Karstic morphologies are very scarce, with limited areas of karren and some small caves (Andreo et al. 1997). Hydrogeologically, the direction of groundwater flow is from West to East, where the main points of natural discharge (Torremolinos springs) are located. Hydrograph analysis of these springs shows a system with diffuse flow behaviour (Andreo et al. 1997; Andreo and Carrasco 1999).

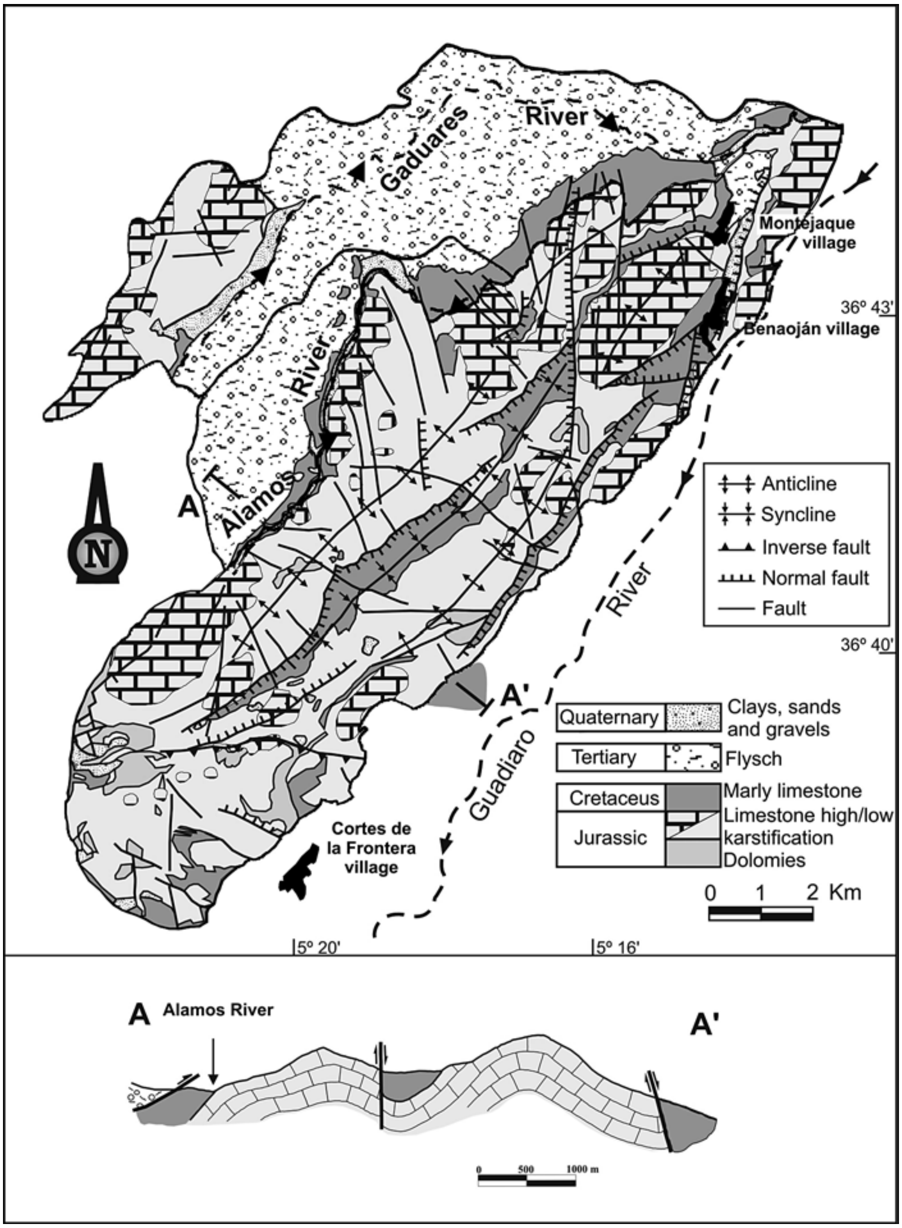
Vulnerability maps using the COP method

The COP map of the Sierra de Líbar aquifer (Fig. 5a) shows high vulnerability throughout most of the system, due to the high degree of karstification of the carbonate outcrop. This high degree of karstification favours rapid infiltration from the surface to the saturated zone (Andreo et al. 2005).

Within the carbonate outcrop, the *O* factor determines Very High vulnerability in areas where the thickness of the unsaturated zone is less than 250 m, as in the NW edge of the aquifer (Fig. 5a). The *C* factor determines elevated vulnerability in areas where infiltration processes are dominant rather than runoff, i.e. areas where karst landforms are not covered by impermeable layers or areas where the karst is not highly developed and the slope/vegetation favours infiltration. These areas can be small, consequently the map shows many small zones of very high vulnerability. The poljes within the aquifer are classified as Very High vulnerability due to the presence of swallow holes that result in rapid travel times bypassing the protection offered by the unsaturated zone. The lowest vulnerability areas correspond to outcrops of Cretaceous marly-limestones, where both this low permeability material and the prevailing slopes promote runoff towards the edge of the aquifer.

In the Torremolinos aquifer, the COP vulnerability assessment (Fig. 6a) indicates higher protection than in the Sierra de Líbar aquifer. This lower vulnerability is mainly due to limited karstification of the carbonate rocks, which diminish the influence of the *C* factor with the protection provided by the dominant *O* factor. The distribution of vulnerability zones is relatively homogeneous. The main vulnerability classes are Moderate and High, which reflect the total lack of soil and the dominance of unsaturated zone thickness in the assessment. Moderate vulnerability is assigned where the unsaturated zone is greater than 300 m and high vulnerability where it is less than 300 m. The Very High vulnerability areas are found at outcrop where the unsaturated zone thickness is less than 85 m. The Low and Very Low classes occur where layers of low permeability material, such as the Plio-Quaternary deposits overlay the aquifer at its northern and eastern boundaries, similarly where Paleozoic metapelites overlay the aquifer on its south-western boundary.

Fig. 3 Map of Sierra de Líbar aquifer (and adjacent area to the north west) showing the main lithological, geomorphological and hydrogeological features



Vulnerability maps by other methods

Figures 5 and 6 show the results of several other methods of vulnerability mapping in the two pilots aquifers, these are DRASTIC (Aller et al. 1987), GOD (Foster 1987) and AVI (Van Stempvoort et al. 1993). These methods have been successfully used in many aquifers worldwide and they were applied in this study in order to compare the results obtained with the COP method.

In the Sierra de Líbar, the DRASTIC map (Fig. 5b) displays High (but not Very High) vulnerability throughout most of the area, due to the scarcity of soils and the highly karstified nature of the limestones and Moderate vulnerability in the poljes. The GOD method (Fig. 5c) shows Moderate vulnerability throughout most of the study area, where the highly karstified limestones outcrop, and Low vulnerability in the poljes where Cretaceous marls appear, even when the swallow holes result in rapid infiltration of stream flow. The AVI map (Fig. 5d) shows High vulnerability in the majority of the aquifer, due to the high hydraulic conductivity of the karstified limestones, and Low vulnerability in the poljes. From this it is apparent that in karstic aquifers such as the Sierra de Líbar, conventional methods of vulnerability mapping do not adequately assess vulnerability, especially where poljes and swallow holes are prevalent.

In the Torremolinos aquifer (Fig. 6) all methods of vulnerability assessment show a similar distribution of spatial variability, i.e. Low vulnerability in areas overlain by the Pliocene-Quaternary marls and Moderate to High vulnerability in areas of Triassic marbles (Longo et al. 2001; Vías et al. 2005). The "High" and "Very High" degrees of vulnerabilities obtained with all the methods, coincide with zones where the water table is closer to the ground surface. For all the methods, the parameters relating to lithology

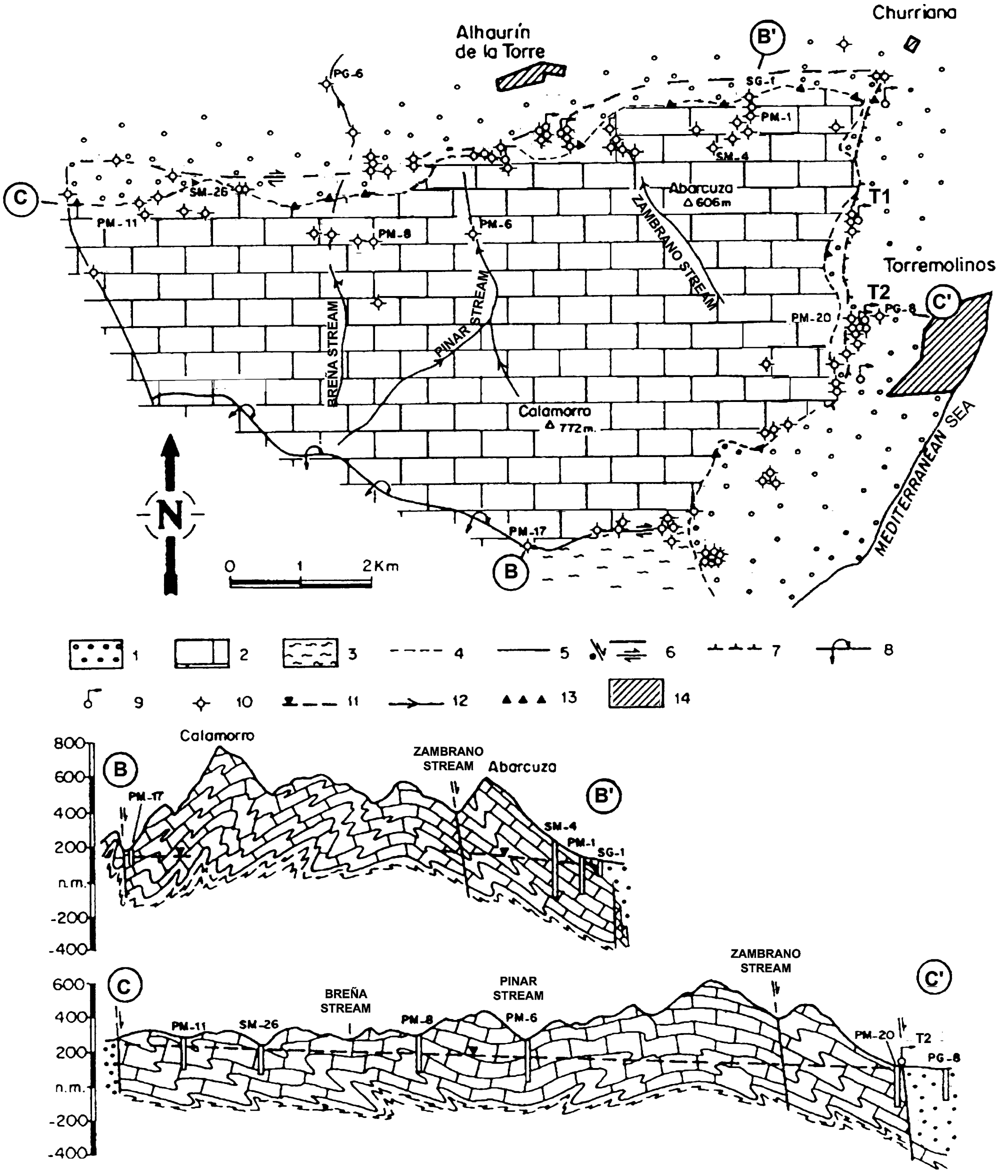


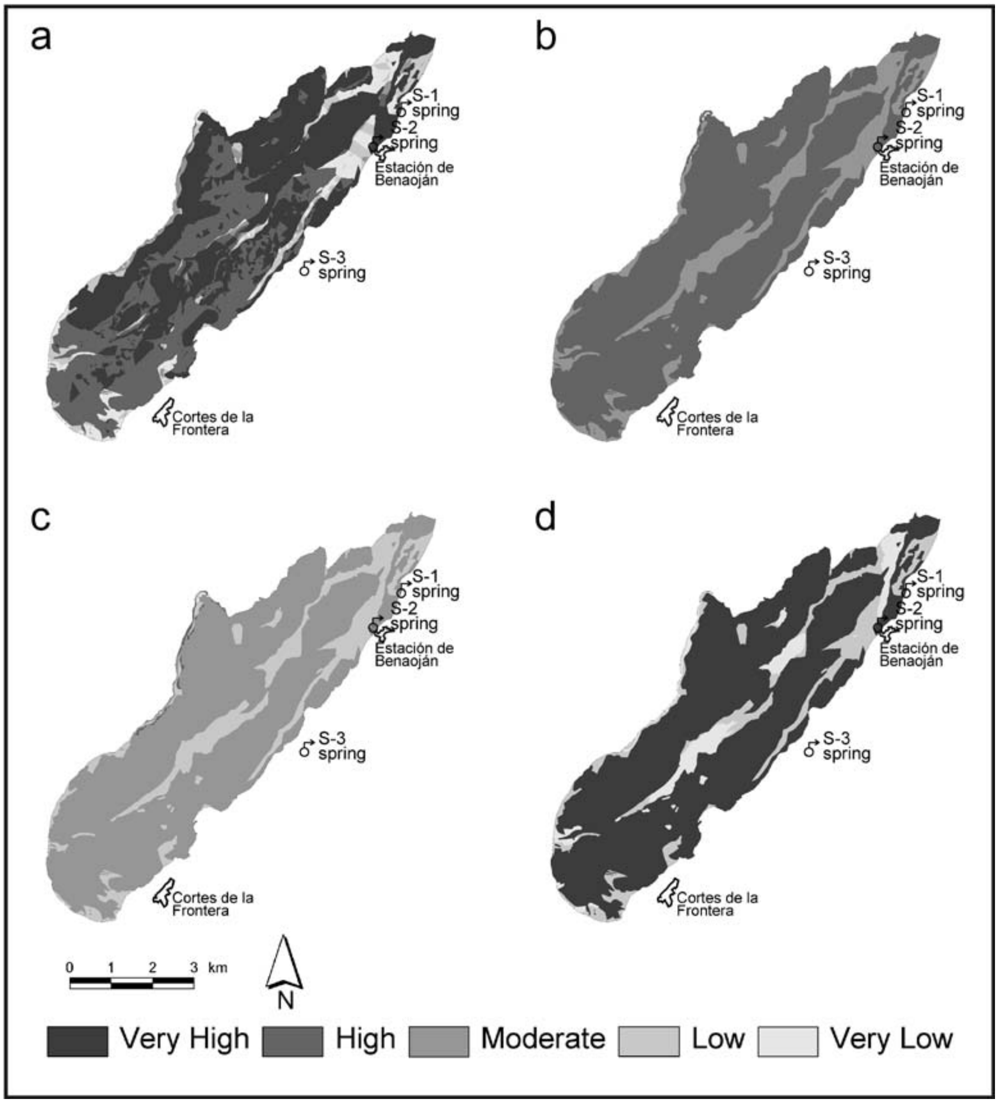
Fig. 4 Map of Torremolinos aquifer showing the main lithological and hydrogeological features (after Andreo 1997). Legend: (1) Plio-Quaternary sediments, (2) Marbles, (3) Metapelites, (4) Unconformity, (5) Fault, (6) Strike-slip fault (7) Normal fault, (8) Reversed anticline, (9) Spring and its reference, (10) Well, (11) Water table, (12) Watercourse, (13) Possible transfer of groundwater, (14) urban areas

are most relevant, whilst the depth to the water table has less influence. The “Moderate” vulnerability indicated by the DRASTIC and GOD methods (Fig. 6b and c) coincides with that for the marbles. The AVI method (Fig. 6d) reports higher degrees of vulnerability than other methods. However, the Very High vulnerability indicated in the areas of marble are not confirmed by the known characteristics of the aquifer (Andreo et al. 1997; Andreo and Carrasco 1999), namely a thick unsaturated zone and low hydraulic conductivity which results in diffuse flow. The Torremolinos aquifer shows diffuse flow behavior (Andreo et al. 1997; Andreo and Carrasco 1999) with rainfall infiltrating slowly because, whilst the marbles are highly fractured, they are poorly karstified.

Figure 7 is a histogram that allows comparison of the results obtained from the four vulnerability mapping methods used in both aquifers. Of the methods used, the COP method provides the greater differentiation in vulnerability classes in both aquifers. This results from using factors that address not only lithology but also the influence of karst features on infiltration (diffuse or concentrated) as well as rainfall distribution. In addition, the maps obtained using the COP method are in better agreement with current hydrogeological understanding of the pilot aquifers.

Apart from the DRASTIC, GOD and AVI methods which have been applied by the current authors to both study areas, vulnerability studies have been carried out in the same areas by different workers. The other methods used were SINTACS (Longo et al. 2001), EPIK and PI (Brechenmacher 2002; Vías et al. 2005; Andreo et al. 2005). Each of these studies concluded that the COP method was the most effective at assessing the prevailing vulnerability of these aquifers based on actual hydrogeological understanding of the aquifers.

Fig. 5 Vulnerability classes obtained with the (**a**) COP, (**b**) DRASTIC, (**c**) GOD and (**d**) AVI methods, mapped for the Sierra de Líbar aquifer



Validation of intrinsic vulnerability maps

After vulnerability maps are produced, they should be validated in order to estimate the validity of the conceptual understanding of prevailing hydrogeological conditions (Bruyère et al. 2001; Jeannin et al. 2001; Goldscheider et al. 2001; Perrin et al. 2004). Several tools can be used for the validation of vulnerability assessments (Zwahlen 2004); these include hydrographs, chemographs and tracers (natural or artificial). Conservative tracers (i.e. isotopes of the water molecule) or near conservative ones (i.e. fluorescent artificial tracers) are the most reliable. Some of these techniques have been used to validate the vulnerability maps of the pilot sites.

Sierra de Líbar aquifer

Tracer tests have been carried out at the Sierra de Líbar pilot site using artificial tracers (Eosine, Uranine and Sulforhodamine-B) in order to validate the intrinsic vulnerability maps (Andreo et al. 2004). The three tracers were injected in three swallow holes (P-1, P-2 and P-3, respectively, in Fig. 8a) during a period of high water conditions, when sinking streams were active. The results show the travel time of tracers from the injection point to arrival at a principal spring to be 3–5 days (Fig. 8b–e) and, as a result, the travel time through the unsaturated zone can be assumed to be less than 3 days. However the results of the tracer tests are only valid for contaminants entering the swallow holes used to inject tracer and not for the whole of the aquifer.

From the tests, flow velocities were calculated to be higher than 43 m/h (connection P-2 with spring S-2) with a maximum velocity of 119 m/h (connection P-3 with S-4). These data confirm the high vulnerability of the Sierra de Líbar aquifer, particularly when surface water infiltrates into swallow holes (injection points). These points correspond with the Very High vulnerability class used within the COP method (Fig. 5a).

In addition, the tracer tests also confirmed that if a potential conservative contaminant infiltrates into P-1 and P-2 swallow holes, then the springs S-1, S-2 and S-3 would

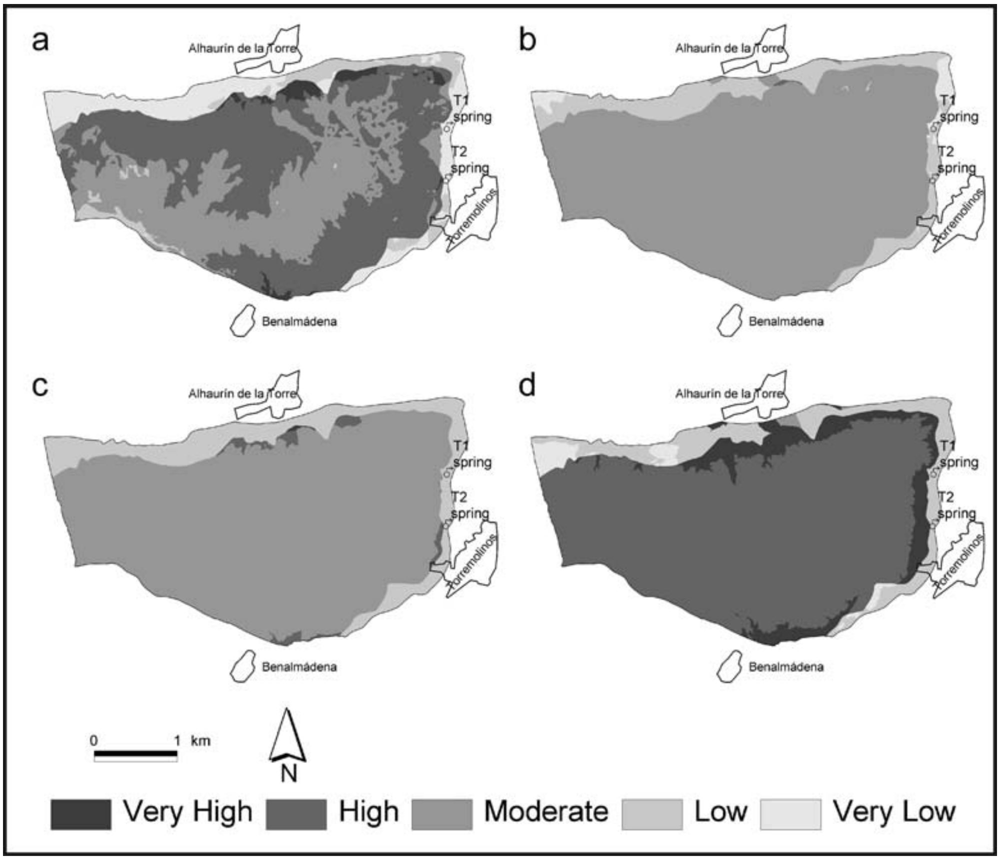


Fig. 6 Vulnerability classes obtained with the (**a**) COP, (**b**) DRASTIC, (**c**) GOD and (**d**) AVI methods, mapped for the Torremolinos aquifer

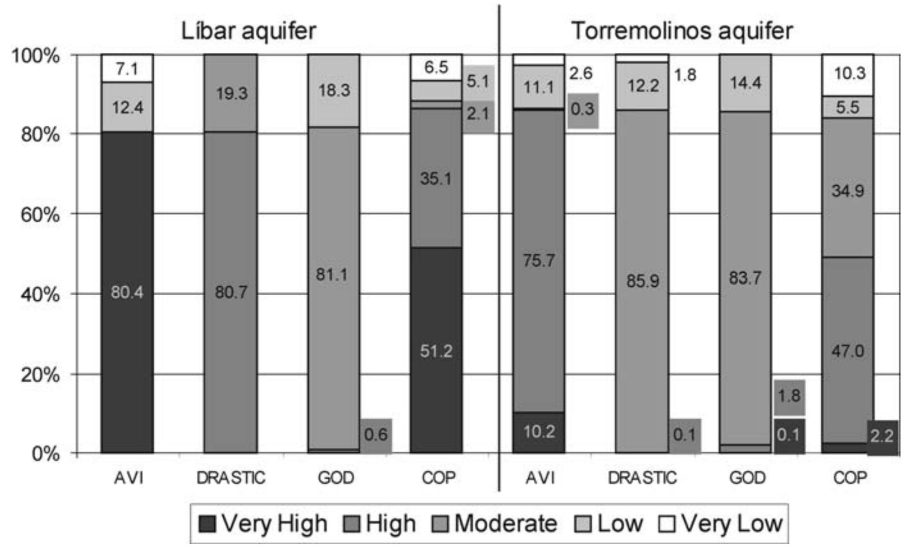


Fig. 7 Percentage surface area for each vulnerability class in the Sierra de Líbar and Torremolinos aquifers using different methods of assessment

be affected (Fig. 8b–d). However, if contaminant infiltrates into P-3, only the spring S-4 would be contaminated (Fig. 8e). So, the three swallow holes are highly vulnerable according to the vulnerability maps, but the impact of a contaminant on a spring would depend on the location of the injection point. The water quality of Guadiaro River would be affected by a contaminant infiltrated into the Sierra de Líbar aquifer via any of the tested swallow holes. This emphasises the usefulness of tracer tests as a tool to develop better hydrogeological understanding of karst aquifers. On the other hand, electrical conductivity (EC) which is indicative of the overall mineralisation of groundwater discharging from springs, as well as the isotopic signal of oxygen in rainfall and groundwater, are hydrochemical tools for the validation of vulnerability mapping. For that reason these parameters were monitored in the springs S-1 (EC), S-2 (EC and $\delta^{18}O$) and in the rainfall ($\delta^{18}O$) (see location in Fig. 8a).

Recharge events reach the springs very quickly (less than 3–4 days after the rain) producing rapid increase

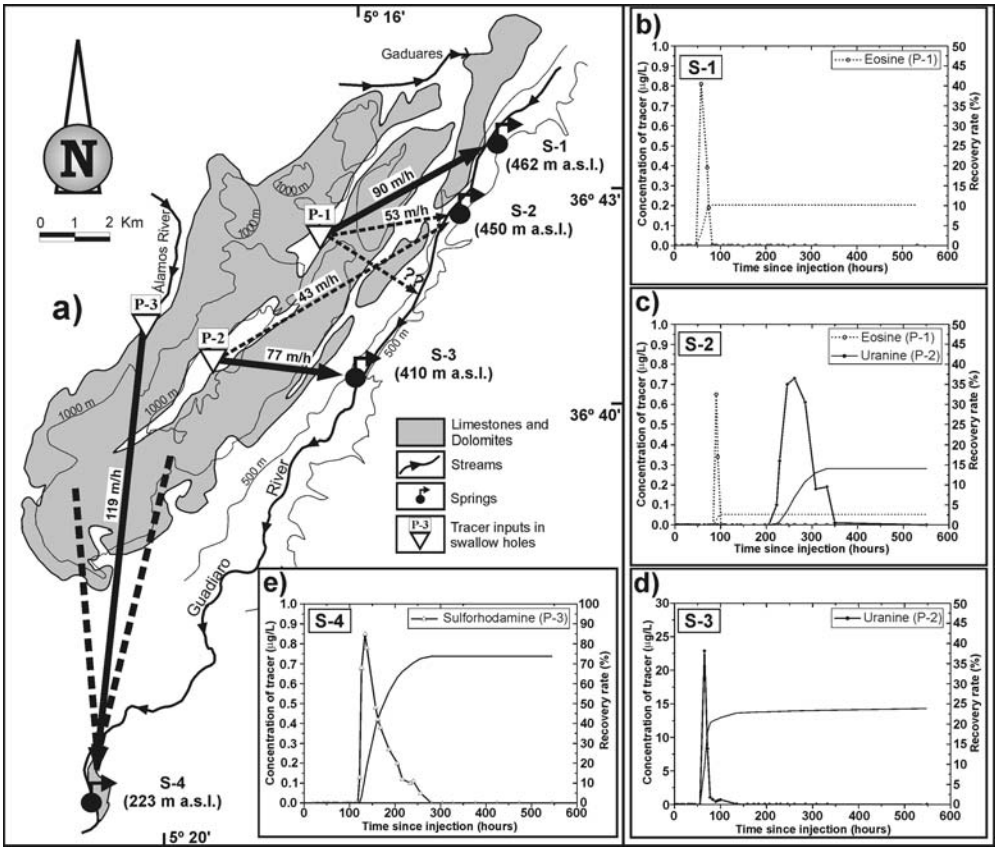


Fig. 8 (**a**) Direction and travel time (meters per hour) for tracers during tests carried out in Sierra de Líbar aquifer (after Andreo et al. 2004), and results for (**b**) spring S-1, (**c**) spring S-2, (**d**) spring S-3 and (**e**) spring S-4. Fastest connections are indicated with solid black arrows whereas slower velocities or deduced connections are marked in dashed arrows. m a.s.l.: meters above sea level

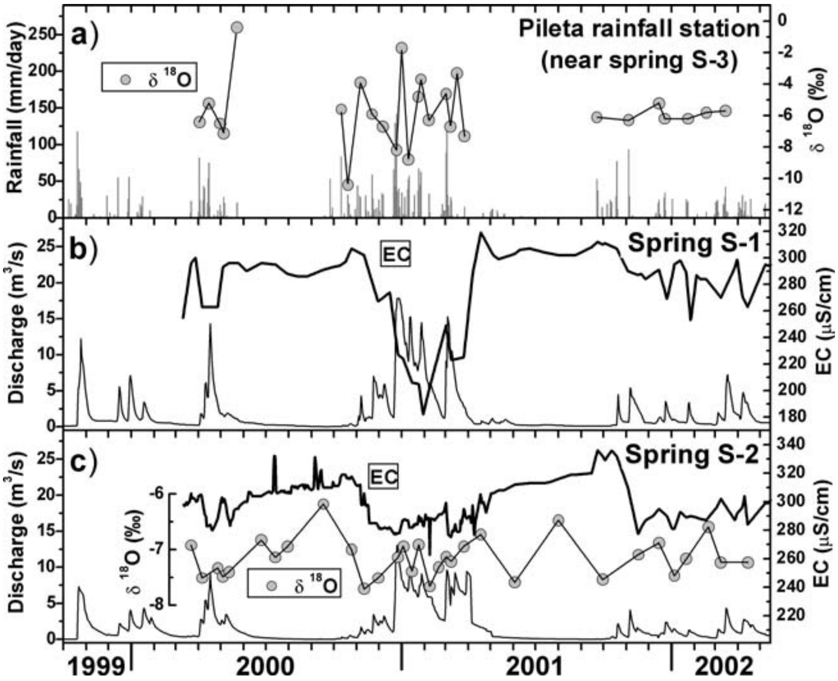


Fig. 9 Temporal evolution of hydrodynamic, hydrochemical and isotope parameters in (**a**) rainfall, (**b**) spring S-1 and (**c**) spring S-2 in the Sierra de Líbar aquifer

in flow, from almost zero to several cubic meters per second (Fig. 9). Hydrograph analysis reveals a fast decrease in spring flow with a depletion curve characterised by an α-coefficient value of around 10^{-2} days^{-1}. Moreover the results of the application of correlatory and spectral analysis reveal a low inertia and the rapid response to rainfall (Carrasco et al. 2001; Jiménez et al. 2004).

The hydrodynamic response of the aquifer to rainfall, decreases the electrical conductivity of groundwater emerging

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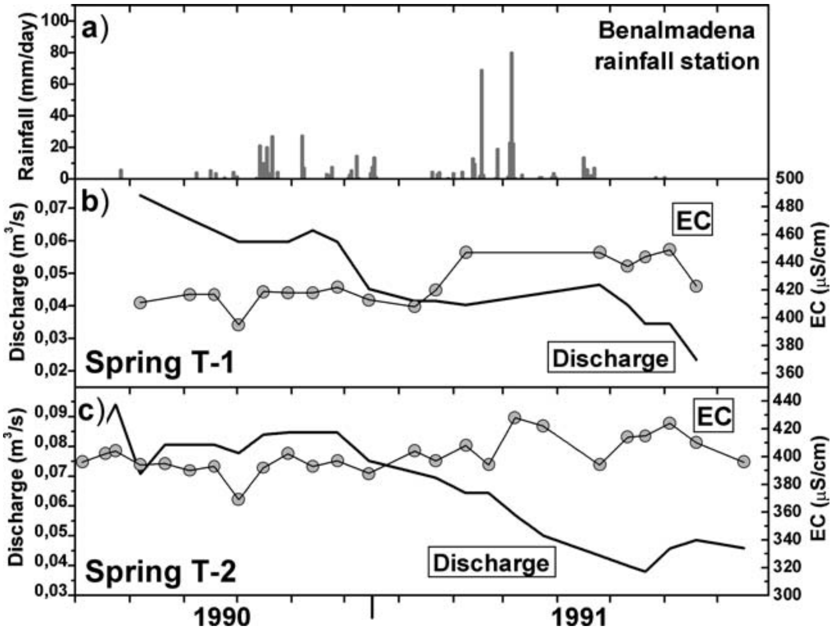

Fig. 10 Temporal evolution of hydrodynamic and hydrochemical parameters in (**a**) rainfall in Benalmadena station, located 6 km west of the springs, (**b**) spring T-1 and (**c**) spring T-2 in the Torremolinos aquifer (from historic data)

from springs (Fig. 9) to between 50 µS/cm (Spring S-2) and 120 µS/cm (Spring S-1). Rapid reductions in electrical conductivity are detected after each recharge period; however the lowest values are recorded several weeks after the maximum flow rate. This suggests that transit times are short due to the development of karstic drainage (conduit flow) within the calcareous rocks of the Sierra de Líbar aquifer (Jiménez et al. 2004), although the influence of recharge in the aquifer is longer than was suggested by the tracer tests. These data demonstrate that the hydrochemical response in the springs result from the whole of their catchment area and not simply from point sources (i.e. swallow hole); the spring catchments can be seen to integrate areas of the aquifer which have different vulnerability classes (not only Very High).

Analysis of the isotopic contents of the area's rainwater and groundwater from spring S-2 supports the observations made from analysing the hydrodynamic and hydrochemical responses of the aquifer (Jiménez et al. 2004). The conservation of the rainfall signal within the hydrodynamic response of the aquifer, as observed at a spring, is indicative of rapid infiltration of rainwater without significant mixing with groundwater within the satured zone.

Artificial and natural tracers demonstrate the high vulnerability of the Sierra de Líbar karst aquifer, however natural tracers provide information on the entire system and artificial tracers provide information only on selected points. The high vulnerability of the Sierra de Libar aquifer, as assessed using the COP method, is consistent with actual known episodes of groundwater contamination. These episodes are normally short in time and are detected where water is abstracted from the aquifer to supply the village of Benaoján (see Fig. 3).

Torremolinos aquifer

No tracer tests have been carried out in the Torremolinos aquifer, however data from natural tracers are available. Historical discharge data from the Torremolinos springs (T-1 and T-2 in Fig. 10) show an absence of sharp peaks in the hydrograph and high flows occurring several months after periods of high rainfall. The spring discharge responds slowly to rainfall due to the great hydraulic inertia of the system. The analysis of historical hydrographs show that infiltration occurs slowly and that the springs may remain in a state of depletion ($\alpha = 10^{-4}$ days^{-1}) for several years (Andreo 1997). Correlatory and spectral analysis corroborates the observation that the system possesses a high inertia. More recent recharge periods have not modified the decreasing trend in the hydrograph due to groundwater abstraction. Electrical conductivity data from the springs show a narrow range of variation (Fig. 10b and c). Tritium data from the springs indicate that some of the groundwater abstracted in the Torremolinos area during 1994 originated from recharge which occurred in 1986 (Andreo and Carrasco 1999).

Groundwater within the Torremolinos aquifer shows no evidence of contamination, despite extensive threat from human activity across the whole of the aquifer outcrop (e.g. landfill, waste pipe lines in urban areas and petrol stations). The assessment of moderate vulnerability for the aquifer outcrop, arising from use of the COP method, is supported by independent lines of evidence as well as current knowledge of the aquifer's behavior (Vías et al. 2005). This moderate vulnerability is a result of: a thick unsaturated zone, relatively low hydraulic conductivity, strong hydraulic inertia and therefore diffuse flow behavior.

Conclusions

The COP method has been designed to evaluate the intrinsic vulnerability of the groundwater resource in carbonate aquifers with different degrees of karstification and can be successfully used to consider both diffuse and conduit flow systems, under different climatic conditions (particularly in Mediterranean settings). It takes into account three factors: *C* (flow concentration), *O* (overlying layers) and *P* (precipitation). The *C* factor considers the characteristics of the carbonate (karst) aquifer itself, whilst the *O* and *P* factors can be applied to any other aquifer. The *O* factor reflects the natural protective capability of the overlying layers above the saturated zone to a conservative contaminant. The *C* and *P* factors are used as modifiers to the degree of protection provided by the overlying layers (*O* factor).

In addition, the COP method establishes detailed guidelines, tables and formulae for vulnerability assessment and selects the variables, parameters and factors to be used according to the European Approach proposed by COST Action 620 (Daly et al. 2002; Zwahlen 2004). The method can be applied using geo-environmental data available in most countries, with some fieldwork but without extensive input from geographical information systems (GIS). As a result the COP method is likely to be practical and useful for decision makers implementing groundwater protection schemes.

The COP method has been applied to two carbonate aquifers (Sierra de Líbar and Torremolinos aquifers) with differing hydrodynamic characteristics and climatic conditions. The gradation and distribution of degrees of vulnerability obtained using the COP method are more realistic than that obtained from existing methods and is consistent with current hydrogeological understanding of these aquifers. Validation of vulnerability maps generated using the COP method is enhanced by undertaking tracer tests in different hydrodynamic conditions, injecting tracers not only into swallow holes but also onto outcrop, comparing the results with those obtained using hydrodynamic and hydrochemical tools. The COP method represents a significant step forward in assessing the vulnerability of groundwater within karst aquifers, particularly in Mediterranean type conditions.

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